2.1 Introduction

2.1.1 Advanced Photon Source Facility Description

The APS was designed and constructed to be a major national user facility providing high-brilliance x-ray beams for users from academic institutions, national laboratories, governmental bodies, and industry. The APS uses recently developed insertion-device technology and low-emittance particle beam to produce high-brilliance beams of x-rays.

Figure 2.1 shows a plan view of the APS. The main feature of the APS facility is the experiment hall building, an annular structure with an exterior radius of 191.4 meters, an inner radius of 164.6 meters, and a height of 9.8 meters. The building houses the experiment hall, where x-ray beamlines and experimental equipment are located, and a storage ring contained within a concrete shielding enclosure. Around the periphery of the experiment hall building are laboratory and office modules (LOMs), which provide office and laboratory space for CAT members and independent investigators performing experiments at the APS. A central laboratory and office building (CLO) is located at the northern periphery of the experiment hall building. The CLO houses the facility staff, who are responsible for operating and maintaining the facility and supporting the experimental program. Adjoining the CLO is the multifunction wing, providing facilities for meetings and conferences. Separating the CLO from the experiment hall building is the control center, which provides a central location for controlling the operation of the facility. To the southeast of the CLO is the utility building, which provides the electrical power, deionized water, and other utilities for the APS facility.

The storage ring is contained within a concrete shielding enclosure located at the inner radius of the experiment hall building. The storage ring consists of magnets, vacuum systems, and other equipment necessary to maintain the circular orbit and energy level of a beam of positrons that is circulating within the storage ring. As the positrons are bent around the circular orbit, they release energy in the form of x-rays. The x-ray production can be greatly enhanced by the inclusion of magnetic insertion devices (IDs) in the storage ring. Two types of IDs are currently used: wigglers, which produce very intense x-ray radiation over a wide range of energies, and undulators, which yield pseudo-monochromatic x-ray radiation tunable over a wide energy range at high brilliance. The x-rays are transmitted from the storage ring through beamline front ends (FEs), which provide a means for confining, defining, and/or stopping each x-ray beam before it exits the storage-ring tunnel to the beamline. The beamlines are located in the experiment hall, between the outside of the concrete shielding enclosure and the outer wall of the experiment hall building. The beamlines include shielded enclosures, beam transports containing vacuum systems, optical elements and experimental instrumentation, and x-ray detectors.

2.1.2 APS Operations

The Associate Laboratory Director for the APS is ultimately responsible for the successful operation of the APS. The day-to-day responsibilities for operations are entrusted to two major divisions of the APS,

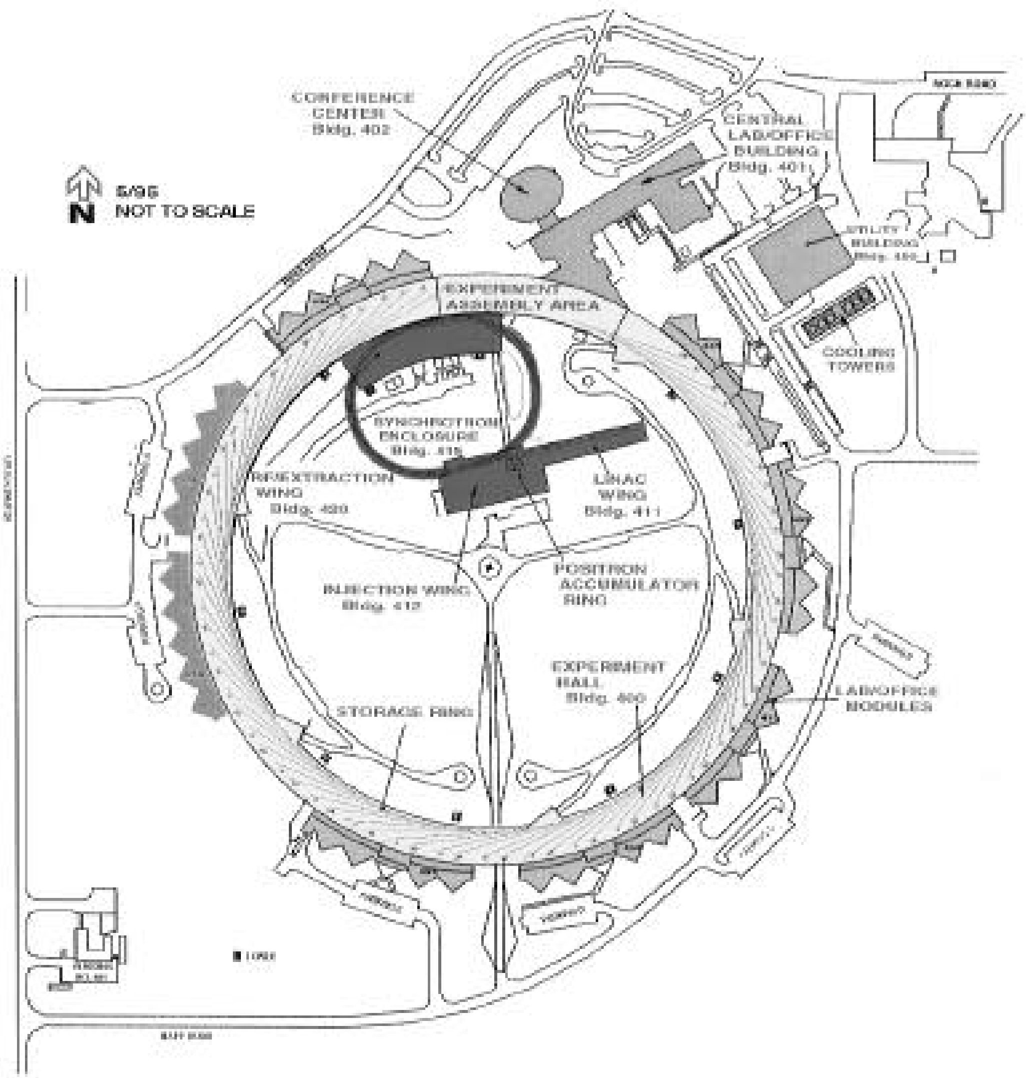

Fig. 2.1 Plan view of the Advanced Photon Source

ASD and XFD. The Accelerator Systems Division has constructed and commissioned the APS accelerators and has responsibility to maintain, operate, and improve the accelerators so as to achieve the highest possible availability and reliability of beam for the user community. The Experimental Facilities Division has constructed and commissioned all IDs, beamline FEs, and all beamline safety systems, and has the responsibility to maintain, operate, and improve the performance of these systems to fully support the users' goals. The principal staff from the Associate Laboratory Director's office, as well as from ASD and XFD, form the Operations Directorate, which meets every week to make all major operations decisions and to determine the operational schedules.

2.1.3 XFD Operations Organization

The XFD Operations Organization is responsible for assuring that the APS effectively meets the operational needs of the user community and for assuring that XFD and user activities conform to the applicable requirements of the Accelerator Safety Order, DOE 5480.25.[1] The XFD Operations Organization has participated with ASD in generating a *Final Safety Assessment Document* (SAD),[2] as required by the DOE order, which provides an evaluation of the level of risk, level of consequence, and the probability of occurrence for the various hazards found at the facility. The SAD also defines the operating safety envelope for the facility. All of the operational activities conform to the requirements as stated in the *APS Conduct of Operations Manual.*[3] In support of APS user activities, the XFD Operations Organization also gathers specific facility operating requirements, integrates the requests, determines the operating modes that are needed to meet the requirements, and works with the ASD to satisfy the requirements. The Operations Organization is under the direction of an Associate Division Director for Operations and includes two major groups: the Beamline Operations Group and the Interlock Systems and Instrumentation Group, as well as support staff to aid the group activities. The XFD Operations organization is shown in Fig. 1.3 (in Chapter 1).

The Beamline Operations Group is charged with the responsibility for installing, operating, and maintaining the IDs, ID vacuum chambers, the beamline FE components, and ancillary systems. The group members have the vacuum, mechanical, survey and alignment, and utility distribution expertise that is needed to keep these components operating reliably with minimal impact on the availability of beam time to the users.

The Interlock Systems and Instrumentation Group is charged with the responsibility for generating and/or supporting the design, installation, testing, and maintenance of the Personnel Safety System (PSS), Equipment Protection System (EPS), and FE instrumentation. This includes any and all documentation, testing, and fieldwork required for supplying the XFD with high-reliability systems. Each system consists of numerous subsystems that are highly reliable and fail-safe. The PSS is a redundant interlocked system that monitors personnel access into beamline enclosures. The EPS is an interlocked system that reduces the risk of damage to FE beam transport equipment. The group is organized into three functional blocks. The Interlock System Design Section provides interlock systems requirements, scheduling, budget/cost development and control, drafting, and project management support. These systems are designed to applicable codes, orders, and standards for such systems. Software is developed in the Software Development Section under the Software Development Plan and conforms to the Laboratory's Software Quality Assurance Plan. The hardware function in the Hardware Design Section relates to the design, systems requirements, scheduling, budget/cost, drafting, and project management support of FE instrumentation.

The support staff consists of engineering support personnel for quality assurance and reliability analysis, as well as a radiation scientist to provide guidance and support to

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[1] *Safety of Accelerator Facilities, DOE Order 5480.25, U.S. Department of Energy, Washington, DC, 1992.*

[2] Advanced Photon Source Final Safety Assessment Document, *APS-3.1.2.1.0, Argonne National Laboratory, Argonne, IL, June 1996.*

[3] Advanced Photon Source Conduct of Operations Manual, *APS-3.1.1.1.0 (Revision 00, Argonne National Laboratory, Argonne, IL, June 1993.*

the facility and users, especially with regard to user shielding needs.

2.2 Beamline Technical Description

2.2.1 Introduction

Generally, an experimental beamline consists of four functional sections. The first section is the source of the x-rays, where x-rays are produced from the circulating positron beam inside the storage ring. The APS provides the x-ray radiation from two types of sources: one is IDs, and the other is bending magnets (BMs), which are dipole magnets of the storage ring. The IDs, located in the storage-ring straight sections, can be further tailored to provide radiation with specific characteristics required by each beamline user. The radiation from the BM source, whose primary function is to maintain the positron beam in a closed orbit, is a white-radiation source with a critical energy of 19.5 keV.

The second section, immediately outside the technical components of the storage ring but still inside the concrete storage-ring shielding tunnel, is the beamline FE section. This section contains safety shutters, photon beam stops, and other components to coarsely define the emerging x-ray beam and, if required, to stop the x-ray beam and provide adequate radiation protection to areas outside the concrete shielding tunnel. Each x-ray source requires an FE, although there are minor differences between the FEs used with an ID and those used with a BM source.

The third and fourth sections of the beamline are located on the experiment hall floor, outside the storage-ring tunnel. The third section contains hard x-ray optical elements, such as crystal monochromators, filters, and/or mirrors, which are designed to handle the power loads and tailor the characteristics of the photon beam to satisfy the user requirements. Generally, these are contained in the first optics enclosure (FOE). The fourth section consists of the experiment stations, which contain experimental instruments; the sample under investigation; any additional optics needed to analyze and characterize the scattering, absorption, or imaging process; and the detectors. The beam transports, which define and shield the beam path between the various experiment stations, are included as required. Some of the photon beams are split, so that each beamline can have multiple branch lines and numerous experiment stations.

An APS sector includes a beamline based on an ID and an adjacent BM-based beamline. The APS provides the x-ray sources and FEs (sections one and two) for each sector. Sections three and four are the responsibility of each CAT, which designs, builds, and operates the beamlines in its sector(s) with funds independently obtained from various funding sources. Each beamline constructed by the CATs will be unique and will support the scientific program planned by the CAT. Similar components may be used in more than one beamline, but these components will frequently have different mechanical, operational, or scientific characteristics appropriate for the research being conducted on that particular beamline.

The x-ray beam produced by an ID or a storage-ring BM and transported through the beamline FE requires some modification before it can be used as an experimental tool. The beam is tailored by optical elements, located at various positions in the beamline to support the CAT's scientific goals. Because an interaction of the full-energy x-ray beam with any material, even air, will result in scattered radiation, the optical elements, as well as all experimental instruments, are generally located within shielded enclosures to prevent access by personnel when the x-ray beam is on. These are referred to as experiment stations. To ensure that radiation levels on the experiment hall floor meet required safety standards, the vacuum beam pipe, through which the x-ray beam is transported, is shielded.

2.2.2 Operational Aspects of IDs

The characteristics of various IDs installed on the APS storage ring are discussed in detail in Chapter 4 (section 4.1). When the construction phase of the project has been completed, 20 IDs will have been installed for providing x-ray beams to the users. Of these, 18 are undulators (most with a magnetic period of 3.3 cm), one is a wiggler with a critical energy of 33 keV, and one is an elliptical multipole wiggler (EMW) to provide circularly polarized radiation in the plane of the positron orbit.

A typical ID is C-shaped, open on the side near the ID vacuum chamber, and closed on the side near the storage-ring aisle. An end view of a typical ID is shown in Fig. 2.2. The ID base is separate from the supports of the vacuum chamber, allowing an ID to be removed or installed without affecting the vacuum chamber and the ultrahigh-vacuum (UHV) atmosphere within it. The vacuum chamber can thus be baked out, the vacuum level certified, and the chamber precisely aligned to the beam center line prior to ID installation and alignment.

The ID is supported from its internal frame on three points by screw jacks. These are used to level the ID and to uniformly center the gap

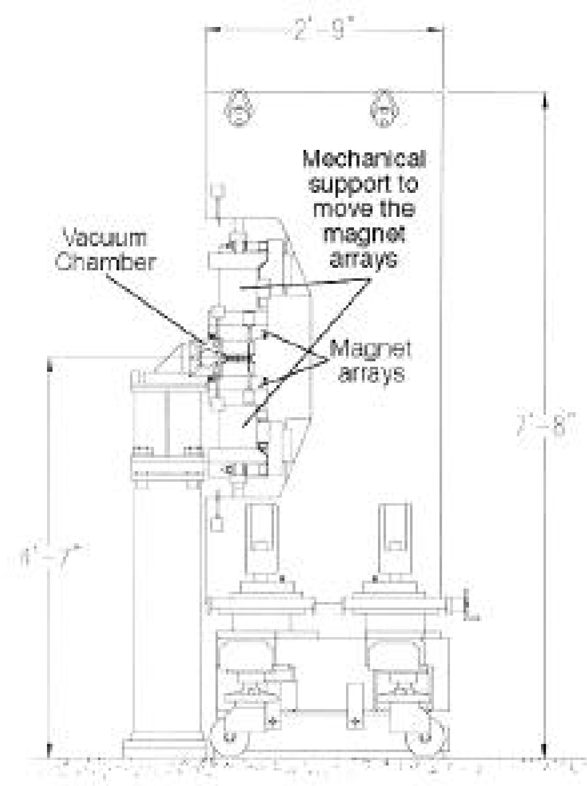

Fig. 2.2 End view of a typical ID

above and below the vacuum chamber. The screw jacks are in turn mounted to dovetail slides, which are used to adjust the horizontal position of the ID relative to the vacuum chamber.

The permanent magnets used in IDs are extremely strong. The support system of each APS ID maintains very precise alignment (better than 10 microns over the length of the undulators) between the upper and lower magnet arrays (each of which is about 2.5 m long) and the ID vacuum chamber. The drive system must overcome the attractive force between the upper and lower magnet arrays; in some wigglers this force may approach 15,000 lbs. The drive system must also position the magnet arrays such that the gap between them can be repetitively controlled with an error of less than 10 microns. The magnet arrays are routinely closed to gaps of

11 mm with a chamber slightly thicker than 10 mm between them. The need to position the magnet arrays as close to the beam as possible and to avoid breaching the vacuum chamber necessitates mechanically fail-safe drive systems. The IDs utilize two independent drive systems, one on the upstream end and one on the downstream end of the device. This allows the gap between the magnet arrays to be tapered. Several levels of safety are also provided by the control system to provide broader energy bandwidths for various undulator harmonics required for specific experiments.

The magnet arrays of the ID sandwich a specially designed storage-ring vacuum chamber (Fig. 2.3). The outside height of the portion of the vacuum chamber located within the magnet arrays is as small as possible to allow the separation between the magnet arrays to be minimized for the largest possible magnet field. The wall thickness of the vacuum chamber has also been minimized. Details are provided in Chapter 4 (section 4.1).

2.2.3 The Beamline FE Operation

The APS beamline FEs are designed to be standard, with one type (Fig. 2.4) for all planned IDs (undulators or wigglers) and another type for all BMs. Depending on the user needs, the ID FEs can be of windowless configuration (with the use of differential vacuum pumps) or of conventional configuration with windows. Normal incidence heat fluxes in the ID FEs at the photon shutter locations are very high, on the order of

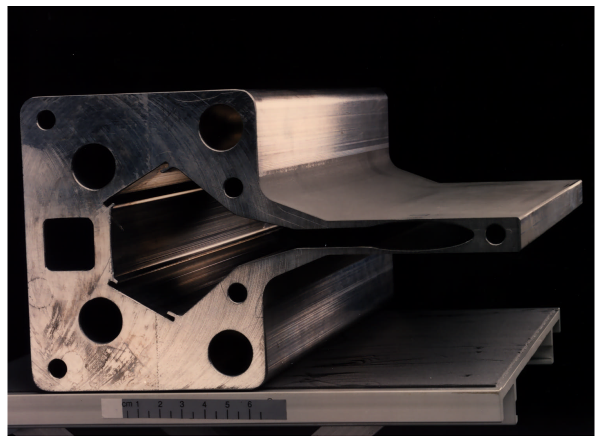

Fig. 2.3 Undulator vacuum chamber cross section

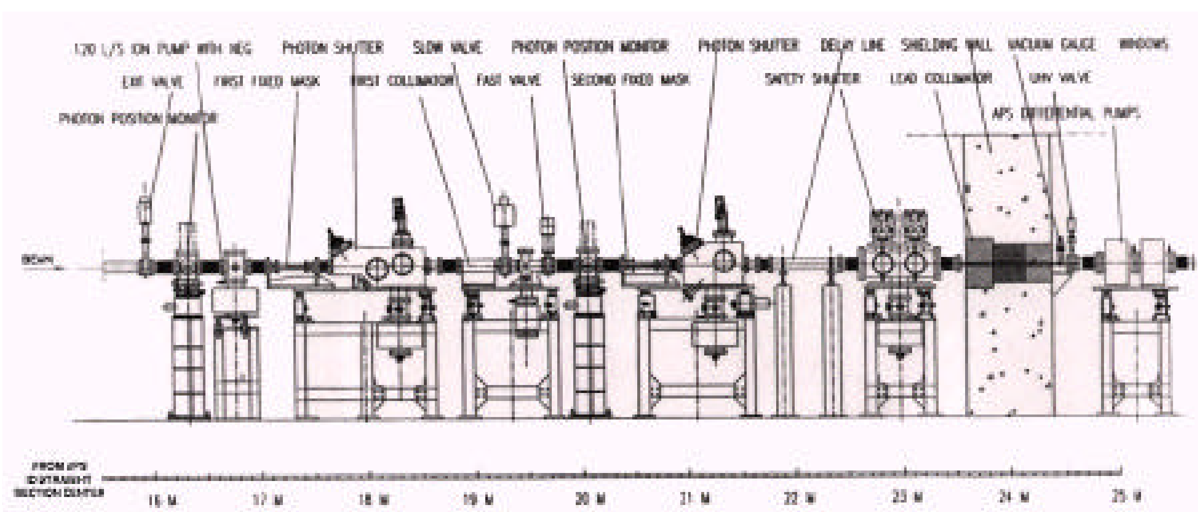

Fig. 2.4 ID front end

450 W/mm^2 or higher. Designing for these fluxes and total heat loads of 10–15 kW posed significant engineering and material challenges. The details of the FE designs have been published.

FE Component Descriptions

In the following, we provide a brief description of the FE components.

Storage Ring Exit Valve: This is a UHV all-metal gate valve that isolates the FE vacuum from the storage-ring vacuum. This valve must be open whenever beam is stored in the storage ring.

X-ray Beam Position Monitor: At the APS, each beamline FE has two sets of x-ray beam position monitors (XBPMs) to monitor the
x-ray beam position and angle. The XBPMs measure photoelectrons generated by the sensory blades and deduce the beam position by comparison of the relative signals from the blades. Compared to the particle beam position monitors in the storage ring, the FE XBPMs have much higher positional sensitivity to the x-ray beam and are more sensitive to angular motion because they are located far away from the source.

For the BM, the vertical position of the beam is critical. The horizontal beam position is not measured, owing to a typical FE acceptance of 6 milliradian of horizontal span of beam. The BM XBPMs consist of two molybdenum blades. The separation of the blades is precisely measured prior to installation. In the case of an undulator beamline, the beam size is small in both the x and y directions, and hence both the horizontal and vertical positions can be measured. Because of the high power from the undulator or wiggler source, chemical vapor deposition (CVD) diamond blades coated with gold are used as blades in the XBPMs (four blades each for undulator FEs and six blades each for wiggler FEs). All the blades in the XBPM are mounted on an oxygen-free high-conductivity (OFHC) copper block using ceramic insulators and are located in UHV. The copper block is water cooled. There are always two sets of XBPMs in each FE to measure both the position and the angle of the beam.

During normal operation of the APS, typical XBPM signals are of the order of microamps. The current signals from the XBPM are brought to a 4/8 channel current amplifier located on top of the storage-ring tunnel. The voltage signals (0-10 V) are in turn fed to display units. The signal is also delivered to the APS control systems via the RS485 interface protocol.

The FE XBPMs are constantly being improved as more operational experience is gained. Some of these details are provided in Chapter 4 (section 4.2).

Fixed-Mask Assembly: This is the first FE component to interact with the beam. The fixed mask may be exposed to the full beam or part of the beam, and therefore cooling and material options must be carefully considered in its design. Each ID FE has two identical fixed-mask assemblies. Water channels are machined into the aperture walls and filled with a porous copper matrix for higher heat transfer to provide cooling.

The design of the fixed masks for BM FEs is similar to that for the ID FEs. Three fixed masks of similar construction are used in each BM FE.

Photon Shutters: This component intercepts the total photon beam to isolate downstream components from the source. The closing time for this device is 0.5 sec. Two of these devices are installed in each FE. In the case of the ID FE, both devices include a “hockey stick” shaped copper absorber blade. The first photon-shutter blade intercepts the beam at a 1.5° grazing angle, and the second photon shutter blade intercepts the beam at a 2° grazing angle. The position of these devices (open or closed) is redundantly indicated by separate switches for each position. The first photon shutter is interlocked to close before the safety shutter closes to prevent a direct beam hit on the safety shutter. It is also interlocked to open only after the safety shutter is opened.

The BM photon shutters are smaller and simpler than those in an ID FE. Preliminary tests have indicated that these shutters are capable of handling the BM radiation from 300 mA of stored beam.

Collimators: The collimators in the FEs define a line of sight to the source and allow a cone of beam to pass through. This device consists of a rectangular vacuum chamber with conflat flanges on each end surrounded by lead blocks to absorb scattered x-rays and bremsstrahlung.

Slow Valve: The slow valve (SV) has the usual function in a synchrotron FE and is an all-metal UHV gate valve that seals to isolate the storage-ring vacuum system from a vacuum breach in the downstream FE or user’s beamline. The closing time is approximately 2 sec. The slow valve is protected by first closing a photon shutter if a slow leak is sensed or by dumping the stored beam in the case of a serious vacuum breach.

Fast Valve: The fast valve (FV) is positioned immediately downstream of the slow valve. This valve closes in approximately 5 msec but does not provide a UHV seal. It provides a low-conductance path that stops a shock wave in the event of a serious vacuum breach downstream. Triggering this device will also trigger the slow valve to isolate the upstream FE and storage-ring vacuum system from the vacuum breach.

Vacuum Delay Line: Because the BM beamline diameter is large, to provide some vacuum delay capability within the BM FEs, eight baffles with apertures are installed inside a 2-meter section of the transport pipe downstream of the fast valve. Such a delay line is not required in the ID FE because of the inherent constrictions in the path.

Safety Shutters: Each FE contains two safety shutters that operate simultaneously; they are used to absorb bremsstrahlung radiation from the scattered particle beam. The absorbing material is UHV-grade tungsten. In the open position, the safety shutters serve a second function as a collimator.

The BM safety shutter is of the same design as the ID safety shutter but with a larger collimator opening.

Front-End Exit Valve: The FE exit valve (FEV) is located immediately downstream of the collimator within the storage-ring shield wall penetration. The FEV is used to isolate the FE vacuum from that in the user beamline. It is pneumatically operated and is controlled by the FE EPS.

Filters: In wiggler beamlines, FE filters are used to give thermal and structural protection to the Be window.

Window: The window is a vacuum separator located in the FOE just after the FEV; it separates the beamline vacuum from the FE vacuum.

Wiggler beamlines are equipped with double Be windows after the FEV in the FOE. During early commissioning, undulator beamlines are equipped with a special device in the corresponding location. This device (referred to as a commissioning window) consists of a pyrolytic graphite foil followed by a water-cooled limiting-aperture mask. The vacuum is terminated by two Be windows.

Bending-magnet beamlines, like wiggler beamlines, are equipped with double Be windows after the FEV in the FOE.

Differential Vacuum Pump: When a user needs unattenuated radiation, a window cannot be used. In such cases, a differential vacuum pump is installed. Using apertures, pressure differentials of greater than two orders of magnitude have been obtained. A delay in excess of 100 msec is achieved when the downstream pressure is allowed to rise rapidly from 2.4×10^{-7} Torr to 1×10^{-4} Torr.

FE Vacuum: Because the FEs are directly coupled to the storage-ring vacuum system, the upstream FE vacuum requirements equal those of the storage ring, i.e., a pressure of 1 nTorr or less with beam on. Achieving UHV conditions requires that hydrocarbons and contaminants be kept to a minimum. Information on UHV pressure is monitored through the use of nude UHV ion gauges, and higher pressure information is obtained through the use of convectron gauges. Mass spectra are also monitored at the downstream end of the FEs, where a residual gas analyzer (RGA) is installed.

The vacuum valve positions are monitored by the EPS, which also monitors the vacuum levels upstream and downstream of each valve. The valves are commanded to close upon detection of a vacuum leak but only if they are protected from direct photon radiation by a photon shutter or an EPS-commanded stored-beam abort. Vacuum breach tests performed on FEs (discussed in Chapter 4, section 4.2) have shown that the FE components perform to specifications.

FE Cooling System: Each FE includes two fixed masks and two photon shutters. These masks and shutters are capable of handling large thermal loads. These components are water cooled. The storage ring consists of two different closed-loop water systems. One is used for components made of aluminum, and the other is for all copper-based components. The water is deionized with a minimum resistivity of 3 megohms. The inlet pressure of the water system is maintained at about 150 psi, while the return is kept at 40 psi. All FE components use deionized water.

In the case of ID FEs, the masks and shutters are made of Glidcop and the water channels are fitted with copper mesh for efficient heat transfer. Because of the mesh in these channels, the pressure drop across each of the components is significant and is measured across each unit. The flow rate is measured for all components.

The pressure drop across a component is measured by using a transmitter. The transmitter is located outside the storage ring to minimize the damage due to high radiation levels. The signals from the transmitter are 4-20 mA current loops. These signals are fed to interface controllers, which are devices that read the current signal and display the flow in inches of water and the pressure in pounds per square inch. These controllers have alarm set points and have level outputs, as well as RS485 communication capability.

2.2.4 Equipment Protection System

Introduction

The APS has overcome a number of design challenges in engineering the FE and beamline components so that they will not be damaged by the thermal loads produced by high power-density x-rays. Another major goal is to ensure that the storage-ring vacuum is not compromised under any vacuum-failure scenario in the FE or beamline.

The FE Equipment Protection System (FE-EPS) monitors and controls devices located in the beamline FEs. Actions taken depend largely on the severity of the fault, ranging from merely setting an alarm, to closing shutters and valves, to inhibiting stored beam. One of the major considerations driving system design was to limit beam aborts and thus contribute to higher operating efficiency of the facility.

Fail-safe principles are incorporated into the design, and the system will lapse into a predetermined safe condition (deenergized to trip) following a failure, including loss of power, air-pressure drop, drop in water flow, shorted outputs, and open circuits.

System Overview

Programmable Logic Controllers (PLCs) are used to handle all system monitoring, control, troubleshooting, and reporting functions. PLCs allow for the design of a very advanced interlock and control system that can handle a large number of distributed I/O points. Each FE is provided with an autonomous EPS that monitors the following parameters: cooling water flow and differential pressure, temperature, vacuum, pneumatic pressure, photon and safety shutter positions, positions of vacuum valves, and status of the systems to which the FE-EPS interfaces. The main FE elements monitored and controlled by the FE-EPS are shown schematically in Fig. 2.5.

The Programmable Logic Controllers

A state-of-the-art platform technology Allen-Bradley processor PLC-5/30 is used. The PLC performs a complete run-time checksum on the control algorithm and sets a fault bit if an invalid checksum is detected. Should this be the case, the system responds by closing FE critical devices and aborting the particle beam.

Interfaces

In order to isolate different power systems, all interfaces between the FE-EPS and other systems and subsystems are implemented through relay contacts. These interfaces are listed in Table 2.1.

Analog Signals

Analog signals are not wired directly to PLC input modules. Instead, microprocessor-based process controllers are used. The controllers accept 4-20 mA current-loop signals from the differential pressure transducers used to

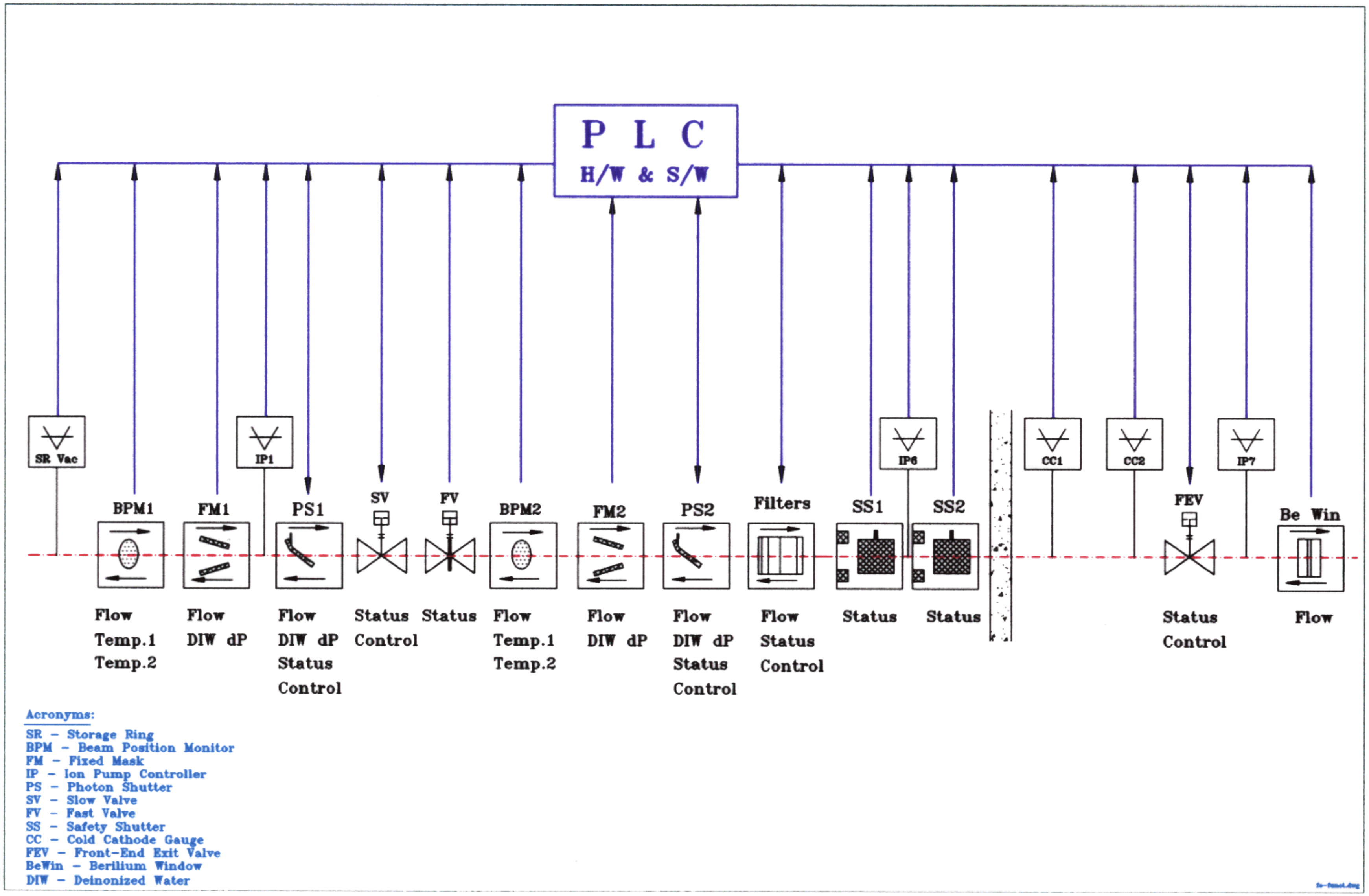

Fig. 2.5 Main elements monitored and controlled by the FE-EPS

Table 2.1 EPS Interfaces and Functions

System	Signal Functions
Personnel Safety	Monitor shutter-open positions Control of photon shutters
Insertion Device	Monitor gap for “max open” status Control emergency gap open
Storage Ring Personnel Safety	Monitor shutter-closed positions Monitor global online/offline
Vacuum System	Monitor SV, FV, CC1, CC2 status Control SV and FEV Permit vacuum controller operation in local mode
Beamline Interlocks	Monitor interlock summation signal and request to close FEV Send FE interlock status, shutter and FEV status
Storage Ring Machine Protection	Control permission to run storage ring RF

measure deionized water parameters and mV-level signals from the thermocouples. Use of the process controllers allows us to change setpoints without altering PLC code and to locally monitor input values from the controller front panel. Each system variable requires its own controller. Controllers are equipped with an RS485 interface, which is used for data collection.

Machine Protection System Interface

One of the challenges faced in the design was the method of protecting the fast vacuum valve from synchrotron radiation when the valve is triggered to close. The valve closure time is less than 7 msec. The PLC alone is not fast enough. The solution is an electronic circuit that interfaces to the vacuum-valve controller, PLC, and storage-ring machine protection system and is capable of aborting storage ring beam in ~2 msec by interrupting a 1 MHz unipolar pulse train.

Vacuum System Controller Interface

A vacuum system controller is capable of monitoring cold cathode gauges (CC) and controlling UHV valves. It can successfully operate as a stand-alone system in a laboratory setting. However, for this application, its capabilities are too limited. By integrating the controller with the PLC, higher system flexibility was achieved, making the controller more intelligent and reducing cost.

Reporting

The status information of the FE-EPS is being incorporated into the APS control system, which is based on EPICS (Experimental Physics and Industrial Control System). This will allow monitoring of the interlock system from the control room and various other locations via operator interface (OPI) consoles. The OPI screens can be called up from authorized X terminals or UNIX work-stations.

Reporting is through a one-way communication protocol, from PLC to APS control system, which allows for displaying EPS status without concern about corrupting the PLC input data table. Graphical displays will include an overall view of the ring and FEs, as well as zoom-in screens for each interlock system. Graphical displays of trending and tabular data of actual values of the transducers (flow, temperature, etc.) are also being planned and developed.

Summary

Currently 36 FE-EPSs are instrumented and operational, and additional systems are being brought on line on a regular basis. The FE-EPS on the BM beamline in Sector 1 has been in operation for ten months. This period has provided valuable operating experience. For example, a number of time delays were fine-tuned, and a 5 sec timer associated with the water interlocks and beam abort was programmed in. Prototypes of the systems have been carefully tested and debugged off-line. Trips observed were all for “legitimate” reasons; most were caused by decreases in the cooling water flow rate to values below the predetermined range. The systems responded the way they should, and there appear to have been no unexplained trips.

2.2.5 The APS Personnel Safety System

Introduction

The APS is designed to operate a maximum of 70 experimental beamlines concurrently. Each beamline includes several shielded experiment stations. Personnel access into these stations is controlled during beamline operation via the APS/XFD PSS. The PSS is an engineered safety system that interlocks personnel access to these stations with x-ray beam-off conditions via beam shutter operation and, if required, storage-ring operation.

The PSS for each beamline is interfaced directly with the Accelerator Systems Access Control and Interlock System (ACIS) to allow the disabling of storage-ring operation. Each beamline has a dedicated PSS that is isolated from all other beamlines to prevent a fault in one beamline from affecting the PSS of other beamlines.

Although there are a variety of beamline designs that reflect the types of experiments being done at the APS, basic PSS configuration and control functions remain the same. If required, specialized user control panels are incorporated into the standard library of PSS hardware.

The PSS is designed to comply with accelerator safety standards in DOE orders and other relevant good practices for accelerator facilities. Among the requirements derived from the above criteria, to which the PSS conforms, some of the more important items are as follows:

- The system is designed to be fail-safe, so that common failure modes leave the PSS in a safe, beam-off state.
- The designs incorporate redundant protection, ensuring that no single component or subsystem failure leaves the PSS in an unsafe condition.

- Provisions for testing are included, so the proper component and system function may be verified.

- Access and egress controls are incorporated so that personnel are not exposed to x-ray radiation. These include emergency shut-off devices, status signs, search and secure procedures, and emergency exit mechanisms.

- A strict configuration control system protects documentation, circuits and software against unauthorized and inadvertent modification. Critical devices are clearly labeled to note that tampering is strictly forbidden.

PSS Description

The PSS provides system-wide (redundant) access control by employing two independent levels of interlock protection, referred to as chain A and chain B. Reduction of common cause failures is achieved by the use of these redundant chains and diversity in the implementation and functionality of the two chains. The system is tested every six months to ensure proper operation.

The PSS protective logic function is implemented in the form of PLCs. A summary of the PSS functionality is illustrated in Fig. 2.6. Using different types of PLCs for each independent chain provides hardware diversity in the PSS. Diversity of PSS software is achieved by using a different language for each chain. Complexity in APS beamline operating modes is translated to the PSS logic. Thus, PLCs were chosen as the

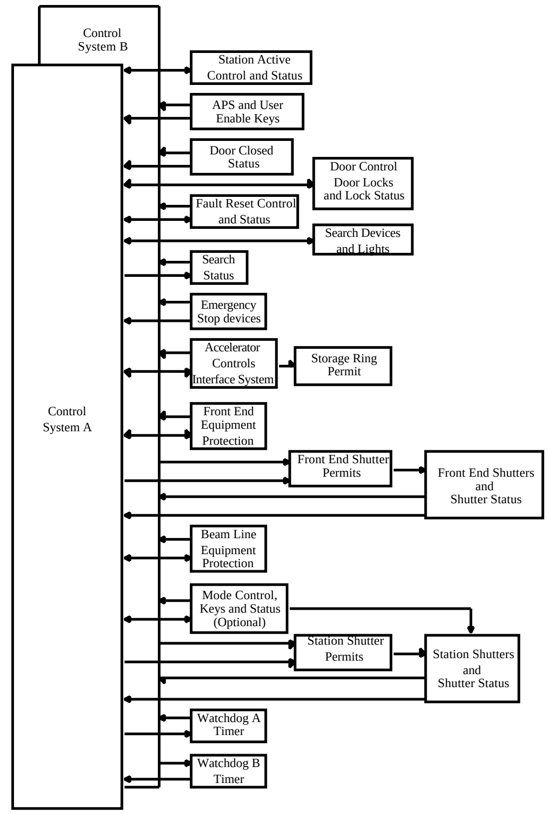

Fig. 2.6 Summary of PSS functionality

PSS hardware platform because they are ideally suited to provide complex protective logic.

The PSS incorporates the following equipment in addition to the PLC hardware:

FE PSS hardware

- Interfaces to the ACIS (for storage-ring shutdown), FE-EPS, beamline EPS, and EPICS (for monitoring and status)

- Interfaces to critical devices that shut down or mitigate the radiation hazards

- Uninterruptible power supply to protect against short-term AC power loss

- Equipment racks, conduit, cable trays and cables

Beamline PSS hardware

- User panels and status displays

- Door position sensors (mechanical and magnetic)

- Door locking mechanism

- Search-and-secure boxes

- Emergency beam stop

- Visible and audible warning indicators

- Interfaces to critical devices that shut down or mitigate the radiation hazards

- Equipment racks, conduit, cable trays and cables

The PSS also provides for external watchdog timer signals between the two PSS chains. If this “heartbeat” signal skips a beat, the PSS will cause a stored-beam abort.

Clearly, the user interface with the PSS involves only beamline hardware. Beamline PSS equipment (to which the user needs access) falls into two categories: user control panels and station hardware. PSS panels, such as door access controls, shutter controls, and mode controls, are in equipment cabinets located on the outside of the experiment stations. These PSS cabinets are locked to prevent uncontrolled access to wiring, but the fronts are open to allow operation of the control panels. These cabinets also contain PLC I/O hardware for each PSS chain. The PSS beamline control panels provide the following user functions:

- a logical visual indication of the beam-line status

- beamline shutter control

- the means to switch shutter control among different stations on a beamline

- the means to change PSS beamline operating modes

- the means to reset PSS faults

- the mechanisms to administratively take stations off-line and bring them back on-line.

The most used of the PSS control chassis is the station control panel, a typical layout of which is shown in Fig. 2.7. This panel is used to open and close safety shutters and provide visible feedback regarding the status of the accelerator, other experiment stations, and the shutters.

The status display consists of a chain of LED indicators laid out in a logical fashion consistent with the beamline layout. Lamps are green if the related devices or systems permit the beam to be propagated down the beamline and are red if configured to stop the beam.

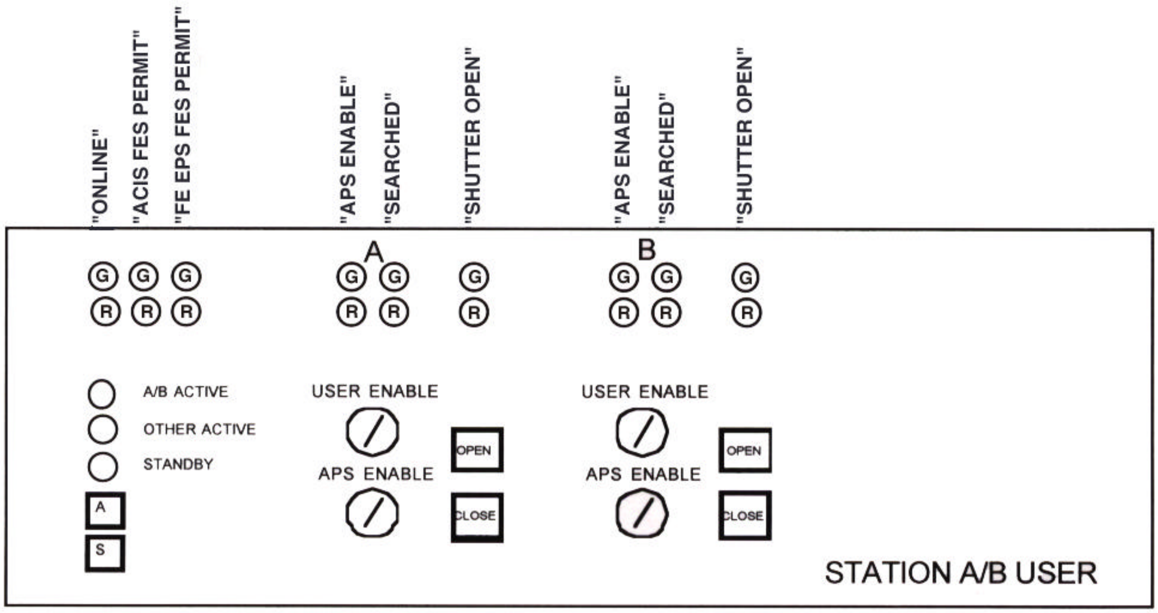

Fig. 2.7 Typical layout of a station control panel

The PSS station hardware provides for emergency beam shutoff and emergency egress. A station search and secure must be completed before beam is transported into a station. During this procedure, the user is forced to depress PSS search buttons in a predetermined sequence and close the station doors within a given time period in order for the PSS to consider the station as secure for beam. Visual and audible indicators are given during the search process. The locations and numbers of search buttons, emergency beam stop buttons, and door open/close buttons are determined by internal XFD safety reviews. At the completion of a successful search, the safety shutters are activated if the other interlock conditions are satisfied. Typical PSS protective logic conditions that need to be completed before opening the safety shutters are shown below:

- Access doors closed
- Station search and secure completed
- Emergency interlocks complete
- Beamline mode selected
- Permits from EPS complete
- APS and user enable keys in a permissive state
- APS storage-ring shutter permit complete

2.2.6 Controls

At the APS, all controls are standardized with EPICS. This system consists of equipment interfaced to VME-based hardware. The VME crate, normally called the IOC (input output controller), talks to the computers via the ethernet. With EPICS, access to the controls is available from any computer located on the same network. This scheme has a great degree of flexibility.

Because of the flexibility provided by EPICS, all data are available at any time to anyone with access to the computer network. There is a separate subnet with restricted access for all the control systems. To provide an added safeguard against unwarranted access to the IOCs, they are all located on this subnet. With the location of an EPICS gateway, data from the control system are provided to other subnets.

In a typical FE, EPICS can currently only read and is not allowed to control. All control actions for the FE have to be performed at locations on top of the storage ring. All vacuum pump and gauge controllers are interfaced with EPICS. The interface enables the ion pump current and the vacuum to be read continuously. All water flow and pressure systems are also interfaced to EPICS via the RS485 interface available in the interface controllers. All data from EPICS are constantly logged to provide for later analysis of specific trends. The constant monitoring of data provides advance warning so that preemptive action can be taken to avoid failures.

The XBPM raw voltage signals for the current amplifier are interfaced to the control system via an RS485 interface. The normalization of the raw signals is performed in the IOC. All signals, both raw and normalized, are available via EPICS.

The ID control is also implemented with EPICS. The ID motor controllers are commanded by EPICS, and the encoders are used to read the precise position of the device. Using the EPICS gateway, added security is provided for ID control to the specific users of a particular beamline.

The PSS and FE-EPS operator/user interface (OUI) is provided for APS facility use. The remote OUI for PSS and FE-EPS has the capability to interface with EPICS. User screens have been developed that graphically represent the PSS status, and the remote OUI does not control any PSS functionality.

2.3 Operations Performance and Reliability

2.3.1 Installation Status

The APS storage-ring design incorporates a magnetic lattice with 35 5-meter-long straight sections available for installation of IDs. The design also incorporates the necessary beam ports for extracting radiation from 35 of the 40 BMs. With each sector containing an ID beamline and a BM beamline, the APS can accommodate a total of 35 sectors. The funding for the APS Project included the funds to construct 20 sectors worth of FEs and IDs available for user research and an additional sector for particle beam diagnostics studies by the APS facility. Installation of IDs and FEs in these sectors is continuing and will be completed by July 1997. A summary of the installation status is shown in Table 2.2. The installation activities are well ahead of the user beamline construction and have not impeded the user beamline commissioning schedule. The remaining 14 IDs and 28 FEs will be built and installed as future funding becomes available.

Table 2.2 Installation and Commissioning Status Summary for User IDs and FEs as of March 1997

	Design maximum	Planned	Installed	Commissioned	Comments
IDs	34	20	17	16	includes 1 wiggler and 1 EMW
ID vacuum chambers	34	20	20	20	
ID front ends	34	20	17	16	
BM front ends	34	20	19	18	

User beamline installation continues at a rapid pace. Although the installation schedule is primarily governed by user funding availability, APS personnel are responsible for managing the installation contracts of the experiment stations and beamline utilities. As of March 1997, 39 experiment stations have been completed on 22 beamlines. Of these 22 beamlines, all have had x-rays delivered to at least the FOE. The dates for the start of commissioning, for each of these beamlines, are shown in Table 2.3. Another 36 stations are nearing completion, and another 23 are at some stage of construction. The current beamline status is shown in Fig. 2.8. By the end of calendar year 1997, all 98 currently planned stations will be completed and all 40 beamlines are expected to be either under commissioning or in operation. Some of the beamlines will not be fully implemented with their full capacity of experiment stations, and as user funding becomes available, additional stations will continue to be constructed on the existing beamlines.

The PSS (as described in section 2.2.5) is the responsibility of XFD personnel. This includes the installation, initial system validation of proper operation, and subsequent revalidations each time an additional station is

Table 2.3 Dates of First Commissioning of APS Beamlines

Beamline	Date of First Beam
1-BM	3/26/95
1-ID	8/9/95
2-BM	6/24/96
2-ID	3/26/96
3-ID	1/24/96
5-BM	3/27/96
5-ID	5/22/96
7-ID	8/16/96
8-ID	8/17/96
10-ID	8/8/96
11-ID	1/14/97
12-BM	3/26/96
12-ID	5/20/96
13-BM	9/17/96
13-ID	9/27/96
17-BM	10/14/96
17-ID	7/5/96
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19-ID	3/26/96
20-ID	12/18/96
33-ID	7/3/96
35-ID	3/6/97

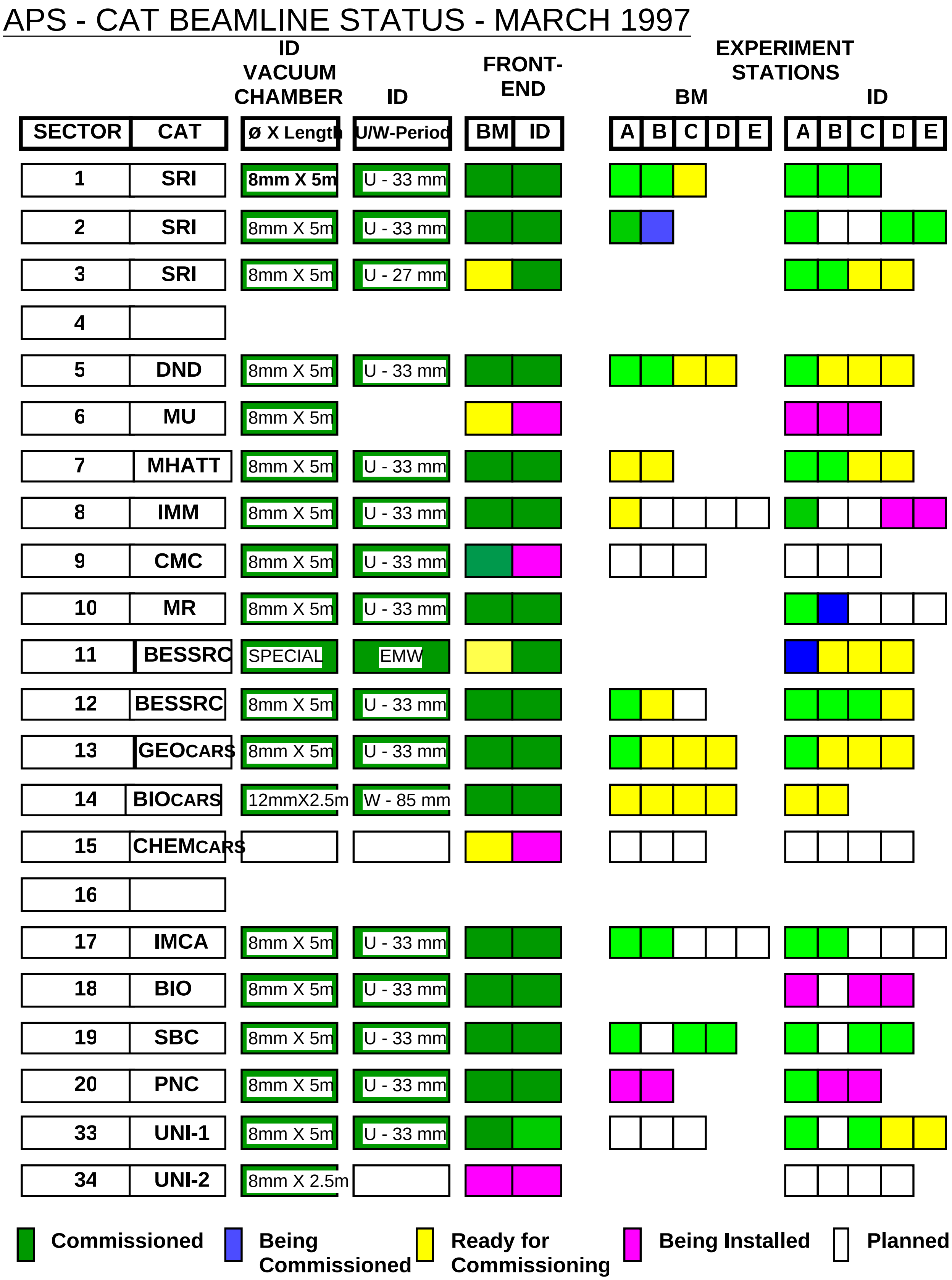

Fig. 2.8 APS CAT beamline status

added to the beamline, each time the control software is modified, or at six-month intervals as required by DOE Order 5480.25. The number of user stations that have been instrumented with the PSS is shown in Fig. 2.9. The figure also shows the number of revalidations performed and summarizes the planned future activities.

2.3.2 Operations Experience

The storage-ring commissioning was begun by ASD on the morning of February 20, 1995, at 5:53 a.m., when a 7 GeV particle beam from the synchrotron was first injected into the APS storage ring. A period of installation and storage-ring commissioning followed. The commissioning consisted of checking out the operation of various systems, adjusting the injected beam orbit, and conducting beam-loss studies. The commissioning activities were limited to night and early morning hours to avoid interfering with construction activities. During this early period of commissioning, adequate radio frequency (rf) voltage was unavailable for storing the beam at 7 GeV. Therefore, the initial stored beam attempts were conducted at an energy of 4.5 GeV. On March 25 at 1:55 a.m., the first stored beam of electrons with a measurable lifetime inside the storage ring was achieved.

At 7:13 a.m. on Sunday, March 26, 1995, the first x-rays from a BM source were delivered down the Sector 1 BM beamline (1-BM) and into station 1-BM-A (FOE). This major milestone took place not only during the centennial of Roentgen’s discovery of x-rays but also within a day of the 150th anniversary of his birth. During the subsequent operating periods, the methodology for measurement of the station shielding integrity was developed. The process is described in more detail later. (See “Shielding Validation of the Experiment Stations” in section 2.4.5.)

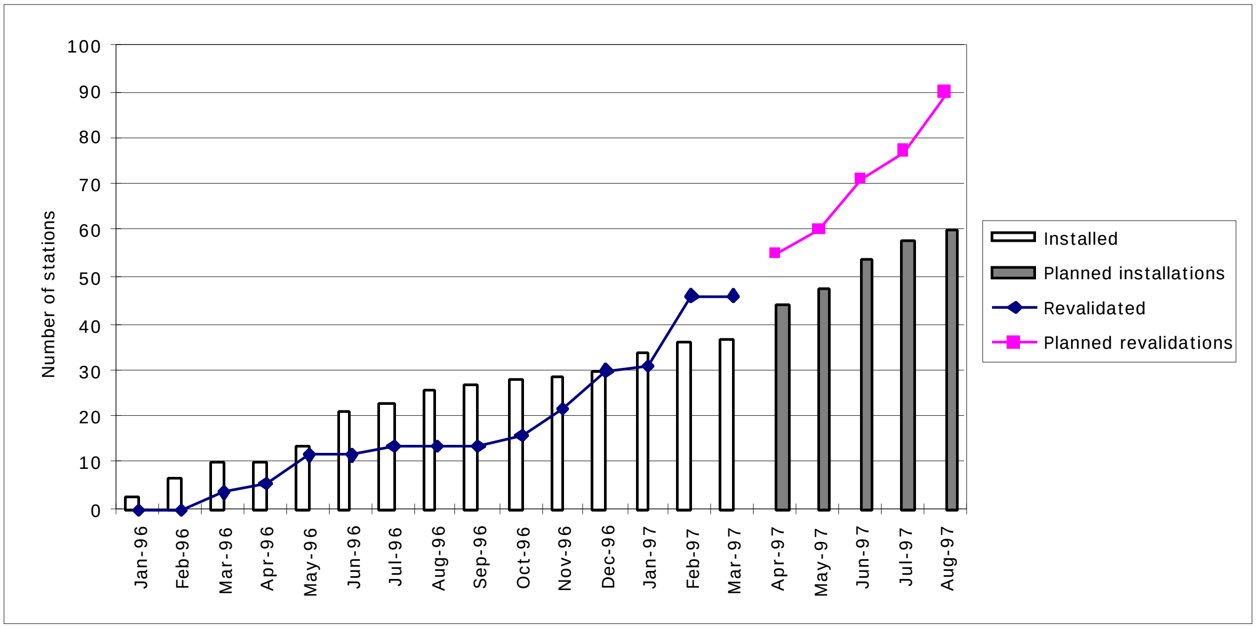

Fig. 2.9 Number of PSS installations and revalidations (completed and planned)

During July and early August of 1995, the first ID vacuum chamber and an undulator A were installed in Sector 1 of the APS storage ring. The vacuum chamber was an initial-phase chamber with a vertical aperture of 12 mm and a minimum possible undulator gap of 14.5 mm. The continued installation of the rf system had also provided adequate voltage for storing the beam at the full energy of 7 GeV. The successful operation of the storage ring in this configuration delivered the first undulator beam to the experiment hall floor of the APS. On August 9, 1995, the photon shutters in the first ID beamline FE were opened, and the first undulator beam was delivered to the FOE on the experiment hall floor. X-rays from undulator A were observed on a fluorescent screen.

After measurement of the shielding integrity of the station, the first experiments looked at the effect of the undulator on a stored 1 mA particle beam. Measurements of the closed-orbit distortion showed that the performance of the undulator exceeded specifications. The results were gratifying because they showed that the undulator fabrication and magnetic tuning had fully met the magnetic field tolerances.

Using electrons, 100 mA of current was stored for the first time on January 26, 1996. On July 31, 1996, 100 mA of current was stored using positrons.

Since that time, a total of 22 beamlines have had the first x-rays delivered to at least the FOE. All beamline work is still at an early stage, consisting primarily of commissioning beamline components, such as monochromators, mirrors, detectors, etc. A few of the stations have conducted scientific research to demonstrate the potential of the APS.

The operating schedule has been optimized to provide adequate and effective time for continuing installation activities, as well as providing time for accelerator studies and user beamline commissioning activities. The storage ring has operated at a 50% duty cycle, with a nominal 3-week-on and 3-week-off cycle. Approximately 30% of the operating time is provided for accelerator studies, with the remainder used for beamline commissioning. Detailed recordkeeping of operating data was started in June 1996. Table 2.4 provides information about the user operating periods (runs) since that time.

Table 2.4 User run statistics

Run designation	96-4	96-5	96-6	96-7	97-1	97-2	
Run start date/ end date	6/22/96 - 7/7/96	8/5/96- 8/19/96	9/17/96 - 10/20/96	12/10/96 - 12/23/96	1/7/97 - 1/25/97	2/25/97 - 3/9/97	
Number of scheduled hours	300.0	324.0	596.0	268.0	376.0	296.0	Σ = 2160.0
Number of available hours	239.8	201.9	456.0	183.0	264.8	206.0	Σ = 1551.5
Availability	79.9%	62.3%	76.5%	68.3%	70.4%	69.6%	$\bar{x}$ = 71.8%

The normal operating mode for user operation is to start with the storage ring filled to 100 mA. Under the present storage-ring operating conditions, the average lifetime at this current is 15-20 hours. The stored beam is dumped when the stored current reaches 50 mA. Storage-ring availability has not yet reached its goal of >90%, with storage-ring faults (primarily from the rf system) often causing beam dumps prior to reaching the 50 mA level. This is reflected in the data shown in Fig. 2.10, which shows the average number of beam fills per day. The distribution of fill duration for each of the runs is shown in Fig. 2.11. Reliability issues relative to XFD components are discussed in the next section.

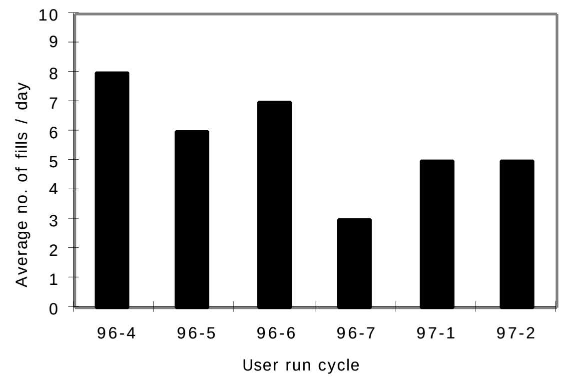

Fig. 2.10 Average number of storage-ring beam fills per day

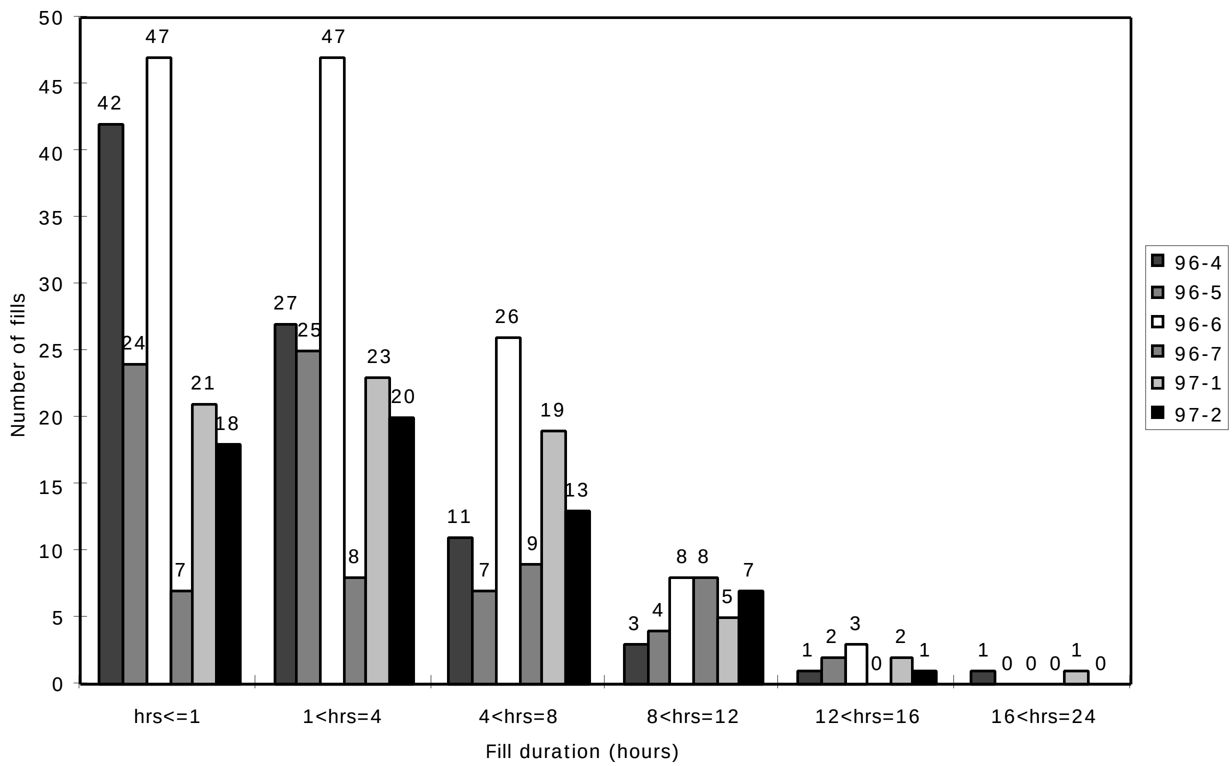

Fig. 2.11 Number of fills with indicated fill durations for the runs shown in Table 2.4

2.3.3 Reliability Studies and Analysis

Statistical data gathering for the APS beamlines began during the third quarter of CY 1996, when an effort was initiated to monitor the reliability of the operational systems down to the component level. This effort is targeted at achieving the following goals:

- Increase availability of beam time to the user community
- Minimize failures and prevent their recurrence
- Predict failures before occurrence

Failures or malfunctions of any equipment required to directly support or operate the beamlines, or which is related to personnel or equipment safety, must be reported and tracked to resolution. Failures are diagnosed and followed up by the cognizant individuals and tracked/analyzed by the quality assurance reliability engineers.

The data required to achieve the above-mentioned goals are gathered by two methods:

1. The controls for monitoring the system performance of the FEs and IDs are located on top of the storage ring with an EPICS interface. All vacuum pump and gauge controllers are interfaced with EPICS. The interface enables the ion pump current and the vacuum to be read continuously. Water flow and pressure systems are also interfaced to EPICS.

   All system/component performance data from EPICS are constantly logged and monitored. This facilitates data gathering and analysis of specific trends and provides the flexibility for advance warning on failures. Problems can then be dealt with in a proactive manner.

2. The life history of each critical component is maintained in the equipment tracking system (ETS), a database system designed to archive key information on beamline critical components. Component data can be entered either electronically with a scanner or manually with a computer and keyboard. In the case of a scanner, unique equipment numbers are generated using ETS and printed onto tags in the form of barcodes. The barcodes are then placed on the component and scanned into the computer. If tag mutilation is possible (due to component bakeout, etc.), the barcode number is engraved on the part directly, and the information is entered manually.

Types of stored information for the components include manufacturer name, component location, drawing number, description, serial number, purchase order number, delivery date, warranty, calibration log, repair log, nonconformance history, and maintenance log. With this information, the ETS can keep a complete history of each individual component from incoming inspection to failure and/or removal from service. In addition, users can be notified of maintenance and calibration requirements of components when applicable. Hard-copy reports of all data are also available to make analysis much easier and more useful.

This database is currently being adapted for use on the APS facility Web pages. The main benefit of this exercise is to make the data more accessible for facility personnel. On the Web, a complete FE or ID component list will be available on-screen simply by clicking on the appropriate sector prompt. A click on a specific component in the list will cause a pop-up window to appear with more detailed information on the component.

Another benefit of adapting ETS to the Web will be the ability to connect the ETS database fields with current XFD Operations Organization Web sites. The XFD Operations Organization is currently employing a failure reporting system called “trouble reports” on the Web. Trouble reports are generated when any problem arises during normal operations. Eventually, the information logged in the trouble reports will be automatically down-loaded into the repair log for the specific components in the ETS. Analysis of this repair data will then be possible and could lead to failure correlations.

In the future, it will also be possible to have the ETS determine maintenance schedules for beam shutdown periods. This could be performed by tying in the ETS maintenance information to a scheduling program.

To date, 32 FEs and 17 IDs are in the operational stage. Failure or malfunction data have been collected on these systems by XFD personnel throughout the construction, installation, and operation phases. The data have been organized into two main groups: (1) critical component rejections during incoming inspection, and (2) failures after component installation. Rejections during incoming inspection are documented via ANL Nonconformance reports and are also entered into the XFD ETS database. Component anomalies after installation are logged in the Web-based XFD Operations trouble reporting system.

Although the operational phase of the APS beamlines is still at an early stage and the numbers of failures documented thus far show no signs of any trends, the failures detected to date are nonetheless being analyzed. For the operational analysis, only components that failed and were either removed from service or repaired and reinstalled are included.

The graph in Fig. 2.12 shows both the number of rejections at incoming inspection and the failures during operations for each quarter starting with the second quarter of 1996. Rejections at incoming inspection do not appear after quarter II, 1996, because the majority of critical components for the FEs and IDs were already inspected at that time. A manufacturing problem with the front-end pressure transmitters led to rejection of 380 units accounting for 41% of the total rejections.

Failures after installation fall into three main categories: mechanical, electrical, and vacuum. Electrical and mechanical failures are the most prevalent, occurring in devices such as PSS/EPS modules, encoders, controllers, and pressure transmitters. To a lesser extent, vacuum leaks have been recognized on FE equipment as well.

Analysis of the statistical data gathered from five beam running cycles indicates the following:

1. With a total of 1860 hours of running time, the XFD Operations systems

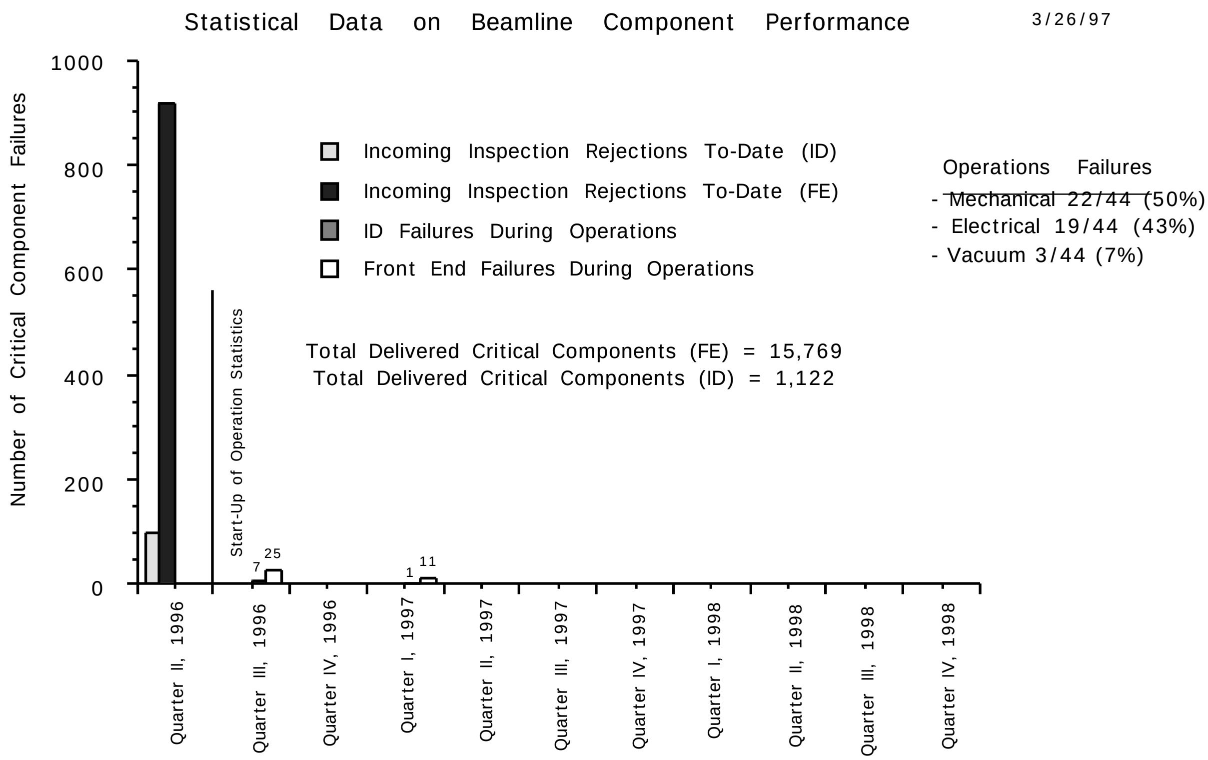

Fig. 2.12 Statistical data on component performance

contributed to 15.3 hours of downtime representing less than 1% of the total downtime. The XFD Operations contribution to x-ray beam downtime during the operational cycles from quarter II, 1996, to quarter I, 1997, is presented graphically in Fig. 2.13.

2. The x-ray beam availability for all systems ranged from 62% (worst case) to 80% (best case).

3. It is still too early to detect any trends in the mean time to failure.

2.4 User Operations Interface and Support

2.4.1 Beamline Commissioning Process

The XFD has instituted a review process to ensure that the beamlines, which are constructed, installed, commissioned, and operated by the CATs, meet the APS facility safety and operational requirements. The process includes reviews through the design, installation, and commissioning phases of the beamlines. All the CATs go through a rigorous set of reviews at various stages of the development of their beamline designs, as

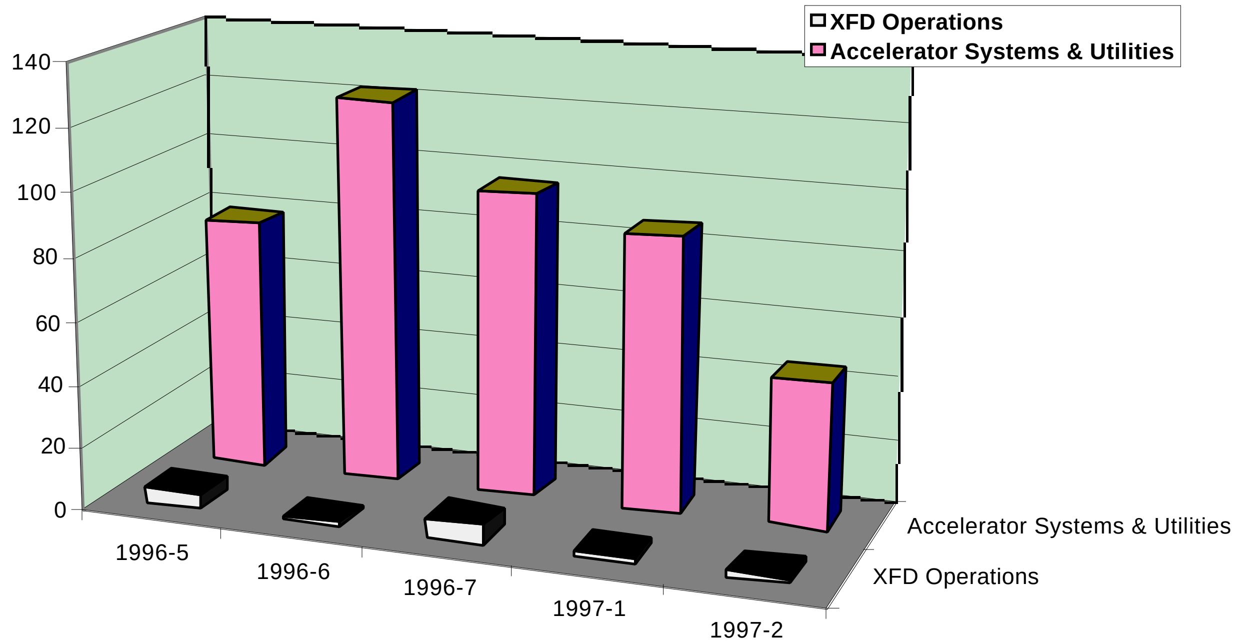

Fig. 2.13 XFD contribution to beam downtime

described in Chapter 3. Before the CATs begin installation of beamline components on the APS experiment hall floor, they have their installation plans approved by the APS as part of the CAT Management Plan. The plan identifies the activities to be carried out on the APS experiment hall floor, personnel involved in those activities, responsibilities of the personnel, hazards associated with the activities, and required training for the personnel. As the installation work proceeds, the CATs begin planning for the commissioning.

The XFD has the responsibility for ensuring that user commissioning activities comply with requirements stated in the Accelerator Safety Order, DOE 5480.25. The order requires that prior to the start of operations, a readiness review be conducted. The XFD has prepared a document entitled *Advanced Photon Source Experimental Beamline Commissioning Readiness Process*, which addresses the process that the APS staff and the CAT personnel will use in commissioning the beamlines. The commissioning readiness review is one of the most critical phases in the beamline review process. Its objective is to ensure that the staged commissioning of the beamline can be performed in a safe and efficient manner. To this end, the process involves the following steps: (a) defining the various stages of beamline commissioning and the commissioning parameters leading to an operational configuration in each stage; (b) checkout of beamline components in each stage; (c) checkout of the required PSS and EPS in each stage; (d) defining the required managerial control systems and procedures and verifying readiness of personnel (both APS and CAT); (e) verifying assignment of responsibilities during the commissioning and verifying that personnel have received appropriate training for these responsibilities; (f) identifying the potential hazards and mitigation methods; and (g) addressing and resolving any interface issues between the CAT commissioning requirements and the facility. To support the validity of the process, the document provides a set of forms that have to be completed and validated by APS and CAT personnel.

The APS is willing to commission a beamline even if only segments are installed and ready for commissioning. On the other hand, if the CAT has installed a complete beamline, it is prudent that the commissioning be done in segments. Commissioning a segment of the beamline at a time spreads the commissioning burden over a longer period.

A typical staged commissioning scenario for an ID beamline is presented here as an illustration:

Stage 1: Commission the FOE (X-ID-A, where X = sector number). This involves commissioning of the ID, the FE, the empty enclosure (X-ID-A, normally the FOE) and the safety interlocks (PSS) required for the safe operation of this enclosure. Either a white-beam stop that is passively safe or a stop that is interlocked to the PSS to shut down the FE is included in the enclosure, depending on the commissioning envelope and the heat loads to be handled. The CAT may suggest the location of the beam dump to reflect a realistic operational configuration of the enclosure. The actual commissioning activity for this stage is described in a procedure; the primary focus here is on validating the shielding and the functionality of the safety interlocks. The XFD also performs photon beam diagnostics during this period, if necessary. The XFD has the prime responsibility for this commissioning stage.

Stage 2: Commission one or more of the instruments (filters, slits, monochromators, etc.) in the FOE (X-ID-A). The primary responsibility for this commissioning stage is with the CAT. When the instrument receives the first beam, XFD supports the commissioning and evaluates the radiation surveys performed by health physics technicians.

Stage 3: Repeat Stage 2, if more instruments are to be added to the FOE (X-ID-A).

Stage 4: Commission the next enclosure, an experiment station (X-ID-B), if it is ready to receive radiation. This phase is similar to Stage 1, and the primary responsibility is with XFD.

Stage 5: Commission instruments in the experiment station (X-ID-B). This is identical to the activities described above during Stages 2 and 3.

In general, additional stages of commissioning will be similar to Stages 4 and 5. There could be deviations from the sequence if the beamline is more complex or if the CAT desires to commission instruments in more than one enclosure in a single commissioning stage. It is also important to point out that in stages involving the commissioning of an enclosure (e.g., Stage 1 or 4 above), the commissioning is performed primarily by the XFD staff, while the instrument commissioning phases (such as Stages 2, 3, and 5 above) are performed mainly by CAT personnel under XFD oversight.

The initial planning of the commissioning stages is done by the CATs and approved by the APS as a part of the CAT beamline commissioning readiness review. The readiness review is conducted by a committee (the Beamline Commissioning Readiness Review

Team, BCRRT), organized by XFD and including CAT representation. Prior to introduction of any beam into the beamline, the BCRRT conducts a visual inspection of the beamline and reviews the APS-conducted test of the PSS interlocks. The BCRRT also develops the beamline operation limits, which are based on the results of the shielding verification and defines the conditions under which the beamline may operate. These include, but are not limited to, the inclusion of hard stops on the ID gap, minimum supplemental shielding requirements, identification of beamline zones that may not be modified without BCRRT approval, etc. The beamline operation limits provide to the Floor Coordinator the necessary information to effectively oversee beamline operation.

The APS Experimental Beamline Commissioning Tutorial Workshop, held on May 16, 1995, described the entire process for commissioning of CAT beamlines. More than 60 representatives from all of the CATs attended the workshop, which was presented by XFD staff.

2.4.2 User Controls

The x-ray beam is available for users during periods called User Operations. During User Operations, once the beam is stored in the storage ring with the correct orbit, the operators in the main control room enable the permit to open shutters. At this point, any CAT whose beamline is ready to operate can ask the APS Floor Coordinator to enable the beamline stations. Once the Floor Coordinator has enabled a station, the user is granted control for the FE and the appropriate beamline shutters. Currently the shutter opening and closing is accomplished from any of the PSS user panels located near each station. The PSS allows shutter operation only when all conditions are satisfied. A system for remote actuation of shutters is being implemented and will allow users to open shutters from additional control locations. When the stored beam is lost, the permit to open shutters is revoked by the storage-ring operators.

In the case of ID beamlines, the users have control of the ID gap during user operation. The control of the ID is given to the specific beamline once the beam has been stored and shutter permit is enabled. Upon beam loss, the ID control is taken over by storage-ring operators and all gaps are opened for injection. Currently the gaps are opened during injection to minimize possible radiation damage to the ID magnets. During mature operation, when all the injection variables have been stabilized, it is expected that injection will take place with all gaps closed. Once injection is complete, the gaps are returned to their last value before beam loss and control is turned over to users

2.4.3 Operations Information Distribution

A major effort is underway to distribute information to the users in a timely manner. Owing to the unified nature of the EPICS control system, thousands of items are monitored at all times. To avoid confusion, careful screening is performed and all relevant information needed for the users' operations is appropriately disseminated.

One of the methods being used is the World Wide Web. All relevant information about the storage-ring status, vacuum, ID status, FE status, and beamline status is available constantly with updates at one- to two-minute intervals. In addition, users can access data for any operating period during the past

90 days in the form of a plot or raw data. A listing of the primary Web pages maintained by XFD is included in Appendix 3.

An EPICS gateway has been installed to provide the users with real-time data at data rates of ~1 Hz. This allows the users to access the data in real time for direct input into their data acquisition systems. A high-bandwidth optical fiber system is being implemented that will provide a direct communication link to the users' control systems at rates exceeding 100 Hz.

A cable TV system with 14-channel capability is being implemented with TV screens located along the perimeter corridor of the experiment hall with expansion capability to the user beamlines and LOM areas. The information to be provided will include operation status, schedule updates, and other information that is pertinent to the user community. This will include *in situ* measurement of beam image and beam stability.

An on-line Web-based system has been implemented to report and track problems occurring with any XFD equipment. This allows the facility to monitor equipment performance, but also permits the user to do correlation studies with possible discrepancies in the collected data. During User Operation, when a problem is observed it is immediately recorded on the Web-based form. The person who responded to the problem in turn completes the Web-based trouble report on all actions taken. The system manager then reviews the trouble report and closes the report. Upon review by the system manager, feedback is given to the originator in the form of an e-mail.

An on-line Web-based system for work requests has also been implemented. No work can be performed by APS staff on any APS controlled system or on any beamline without a properly approved work request. A person planning to work on any system fills out an on-line work request form. If the work includes any components that may have an impact on user operation at a particular beamline, the Floor Coordinators, as well as CAT representatives, are notified of the pending work in that sector. In addition, the CATs at the neighboring beamlines are notified about pending work around their area. If a CAT has any problem with the proposed work schedule, the system manager works with the CAT and rearranges the schedule. Once the work is completed, the system manager closes the work request. It should be pointed out that this system also interacts with ASD personnel if the work requires ASD attention.

All work request forms and trouble reports can be reviewed by any of the users at any time. There are Web-based search engines to review these reports.

2.4.4 User Operations Support

The APS Floor Coordinators are members of the User Technical Interface Group and provide the day-to-day technical support for the APS users. In addition to their support role, the Floor Coordinators provide the primary APS oversight of beamline operations. The Floor Coordinators' offices are distributed around the experiment hall, with each Floor Coordinator assigned to the four sectors that are associated with a specific LOM. Floor Coordinators familiarize themselves with the operation of the beamlines within their areas of responsibility and have the authority to suspend operations if they feel that unsafe conditions may exist. Whenever the facility is operating or whenever beamlines are undergoing significant modification, a Floor Coordinator will be "on duty" representing the APS.

The principal responsibilities of the Floor Coordinators are as follows:

- Act as an interface/coordinator/ expediter between the APS users and the support services of ANL and the APS to facilitate user installation and operation activities. The Floor Coordinators help guide the user through obtaining the service and help to ensure that the work meets the user's specifications and fulfills the requirements of the APS. As users' needs for support from ANL have continued to grow, the Floor Coordinators have worked with the support organizations to tailor their services to meet these needs.

- Work with the APS CATs on the design, installation, and operation of beamline facilities to enhance the safety and the quality of the beamline installation and operations and to ensure that APS and ANL requirements are met. During the past year, a major activity of the Floor Coordinators has been to support installation of beamline utilities. The Floor Coordinators have processed the users' service orders and worked with the contractors and ANL to set up the tools that allow users to monitor the progress of their jobs. Another major activity during the past year has been the support provided to the beamline shielding validation process.

- Provide oversight, in the experiment hall on behalf of the APS, especially of safety aspects of the construction, installation, and operations of APS user facilities. Whenever x-ray beams are being used in the experiment hall, a Floor Coordinator is on duty to oversee the beamline commissioning and operational activities. Also, the Floor Coordinators oversee the beamline configuration controls and manage the work permits for systems that are under configuration control.

- Work with other APS staff members on the development of user support facilities, such as the user LOM machine shops, the liquid-nitrogen supply tanks, and user-related policies and procedures.

During the past year, eight Floor Coordinators have been hired, and their number will continue to increase to support the growing number of beamlines and users. The Floor Coordinator team is being built with personnel who are experienced in a variety of different aspects of the construction and operations of research facilities.

2.4.5 Radiation Shielding and Measurements

Shielding Design Criteria

The APS is a DOE user facility and is subject to all DOE requirements concerning radiation safety. For DOE facilities, the primary document on radiation safety is the *U.S. DOE Radiological Control Manual; Revision 1.*[4]

[4] U.S. DOE Radiological Control Manual; Rev. 1. *Primary Report Number: DOE/EH—0256T-Rev. 1.*

It is a general document that specifies the requirements for many aspects of radiation safety including radiological standards, conduct of work, radioactive materials, training, and record keeping. It is required that new DOE facilities be designed so that the annual integrated dose equivalent received by an individual is no more than 500 mrem.

With the assumption of a 2000-hour working year, this becomes a dose equivalent rate of 0.25 mrem/hr. The value of 0.25 mrem/hr is the criterion used throughout the APS experiment hall to define the operational safety envelope. The beamline shielding, inclusive of the experiment stations, is designed to meet this criterion. The *U.S. DOE Radiological Control Manual; Revision 1* also requires the establishment of an ALARA (As Low As Resonably Achievable) program to guide the design and operation of every radiation-producing facility. Implementation of the ALARA concept is also taken into account in beamline design, commissioning, and operation at the APS.

Shielding Validation of the Experiment Stations

The Experimental Facilities Division, in collaboration with Health Physics personnel from ANL's Environment, Safety and Health (ESH) Division, performs the shielding verification of all the experiment stations. The CATs are allowed to proceed with beamline commissioning activity only after the successful completion of the shielding verification. When a shielding deficiency is detected, the CAT is informed immediately, and activity on the beamline cannot proceed until the deficiency is mitigated.

The purpose of the shielding verification of the APS experiment stations is twofold:

- To confirm that the amount of lead used in the various panels is of sufficient thickness.
- To verify that the joints between panels, wall/floor and door/floor, etc., are radiation tight and do not allow significant radiation to leave the enclosure.

The shielding verification is done for bremsstrahlung, synchrotron radiation, and neutrons. The methodology of the shielding verification is to simulate a worst-case scattering scenario inside the station and to conduct a radiation survey outside the station. In order to do this, worst-case scatterers were designed for each type of radiation.

Bremsstrahlung

Bremsstrahlung produces an electromagnetic shower when it encounters a target. The photon converts to an electron-positron pair, which radiates and, in turn, produces fresh pairs; the number of particles increases exponentially with depth in the medium. This process continues until the particles are below the bremsstrahlung production threshold, i.e., the critical energy of the medium. Then the particles lose energy by ionization, and the shower tapers off. The maximum shower energy occurs at a shower depth of approximately $\ln(E_0/E_c)$ in radiation length of the medium, where E_0 is the initial energy of the photons, and E_c is the critical energy of the medium. Any medium of approximately this thickness simulates the worst-case scattering scenario for bremsstrahlung from the point of view of dose considerations downstream of the scatterer. Table 2.5 shows the depth at which the maximum shower energy occurs for some elements of interest. A smaller thickness of the medium will cause an incomplete shower development, and a larger thickness will attenuate the shower energy.

Because of coulomb scattering, the electromagnetic shower initiated by bremsstrahlung also spreads out laterally. The radial depth of the shower is determined by the radiation length of the medium and the angular deflection of the particle per radiation length at the critical energy. For all materials, this lateral spread of the shower is of the order of one Moliere unit, which is approximately equal to $R_m = 21.1(X_0/E_c)$. Almost 90% of the shower development takes place within a radius of one Moliere unit. Therefore the ideal "worst scatterer" should be of a thickness corresponding to the shower maximum (approximately 5 to 6 radiation lengths) and with lateral dimensions of approximately one Moliere unit. Table 2.5 gives the dimensions of a worst-case scatterer for bremsstrahlung,

Table 2.5 Results of the "Worst Scatterer" Calculations for Bremsstrahlung

Scattering Material	Thickness (cm) X_0*ln(E/Ec)	Transverse Dimensions (2 R_m)
Tungsten	2.5 cm	2.0 cm
Lead	3.8 cm	3.2 cm
Copper	8.3 cm	3.0 cm
Iron	10.0 cm	3.2 cm
Silicon	47.7 cm	9.2 cm
Aluminum	44.7 cm	8.2 cm

one that can be used for the shielding verification.

The worst-case scatterer for bremsstrahlung is also a worst-case source and scatterer of secondary neutrons from bremsstrahlung.

Synchrotron Radiation

Scattering of synchrotron radiation from a target material is determined by three major factors:

- incoherent scattering (Compton) cross section
- photoabsorption cross section
- density of the material

The dimensions of the target for maximum scattering of synchrotron radiation must be optimized with all three factors taken into account. For example, high-Z elements have a larger incoherent scattering cross section and also a larger photoabsorption cross section in the energy range of interest to us (10-500 keV). Therefore, a thick target of high-Z material will have not only good scattering probability but also considerable self-absorption. Table 2.6 gives the photoabsorption cross section and the incoherent scattering cross section at 100 keV for some materials of interest and their ratio. This ratio must be small for a good synchrotron-radiation scattering material. Table 2.6 shows that a target of low-Z material a few millimeters thick (<10 mm), like aluminum, is a good choice.

Table 2.6 Photon Cross Sections for the Target Materials at 100 keV

Material	Photon Cross Section (cm^{-1}) (photo-electric)	(incoherent)	Ratio ($\sigma_{pe}/\sigma_{Incoh}$)
Graphite	0.0014	0.232	0.006
Aluminum	0.049	0.375	0.130
Iron	1.560	1.023	1.525
Copper	2.540	1.129	2.247
Tungsten	74.700	1.854	40.300
Lead	58.300	1.135	51.360

Tungsten is used as the bremsstrahlung scatterer; it is placed upstream of the station so that the scattered shower subtends the maximum solid angle at the back wall of the experiment station. The locations selected for the synchrotron scatterers depend on the configuration of the experiment station. The beam is scattered simultaneously from two scatterers, placed at approximately 1/3 and 2/3 of the length of the station. This placement maximizes the radiation field inside the station. The radiation survey is carried out by appropriately calibrated survey equipment for bremsstrahlung, synchrotron radiation, and neutrons.

Measurement of Gas Bremsstrahlung from the ID Beamlines

Bremsstrahlung is produced in the APS storage ring when the particle beam interacts with the storage-ring components or with the residual gas molecules in the storage-ring vacuum. The interaction of the particles with the gas molecules occurs continually during storage-ring operation. Gas bremsstrahlung is important at the ID straight sections because the contributions from each interaction add up to produce a narrow monodirectional beam that travels down the beamlines. At the APS, with long storage-ring-beam straight paths (15.38 meters), gas bremsstrahlung in the ID beamlines can be significant.

The bremsstrahlung spectrum and the total energy radiated in a beamline are measured by a hermetic lead glass calorimeter. These measurements were carried out at the FOEs of the ID beamlines. The undulator was kept fully open to minimize the synchrotron radiation background. The calorimeter consists of 25 lead glass blocks, each 6 cm × 6 cm × 35 cm in size. Twenty-five phototubes connected to the lead glass blocks collected the signal. The bremsstrahlung spectrum and the total energy radiated were measured as a function of beam current (20 - 100 mA) at 7.0 GeV particle energy for both electrons and positrons. The measurements were repeated at four runs at three different beamlines (12-ID, 10-ID, 13-ID). During data collection, six ion gauges continuously monitored the vacuum in the entire straight section.

The measured bremsstrahlung spectrum was fitted to a function that shows an approximate 1/E behavior. The gas bremsstrahlung rate from the APS undulator-beam straight path of 15.38 m is measured as 60 ± 2 GeV/sec/mA/nTorr. This corresponds to a maximum dose equivalent rate of approximately 4.2×10^{-4} Sv/hr/nTorr/mA. The analysis also shows that there is a significant bremsstrahlung contribution from sources other than the residual gas molecules in the beam straight path in the storage ring. The maximum bremsstrahlung energy rate measured in a beamline is 369 GeV/sec/nTorr/mA, which corresponds to a dose equivalent rate of 2.18×10^{-3} Sv/hr/nTorr/mA.

Measurement of Radiation Dose Received by the IDs

The radiation doses received by the magnetic structures of the insertion devices were found to be a few Mrads for each run. Thermal luminescent dosimeters (TLDs) are inadequate to measure this high dose. A program was initiated to use radiochromic films to measure these doses. Radiochromic films are free-standing films, 40-50 microns thick, of a solid-state solution (nylon). These change color when irradiated, and the dose rates are estimated from the optical density. The range of radiation dose these films can read varies from 10 krad to 100 Mrad.

The radiochromic films were placed at various locations on each of the IDs before each storage-ring run. The films were read initially before being packed in aluminized mylar envelopes to shield them from the UV radiation. A computerized reader was installed to automate the optical-density reading process. After each storage-ring run, the films were collected and read. It was a challenging task to separate the synchrotron-radiation dose from the high-energy gamma dose arising from the particle beam loss at the transition piece between the storage-ring vacuum chamber and the ID vacuum chamber. For this purpose, a multilayer lead stack was designed with radiochromic films placed between intermittent layers. This develops the electromagnetic component of the dose by showering, while the synchrotron-radiation component is absorbed in the first few millimeters of lead. The initial results are very encouraging. These measurements have been repeated for the last several runs. The results are discussed in Chapter 4 (section 4.1).